ASSESSMENT OF THE IMPACT RESISTANCE IN CONCRETE PAVEMENTS REINFORCED WITH VARIOUS KIND OF FIBRES: A COMPARISON BETWEEN COMMON STEEL FIBRES AND NEW POLYMER MODIFIED FIBRES

MICHELE AGOSTINACCHIO, GIANLUCA CUOMO
UNIVERSITY OF BASILICATA – POTENZA – ITALY
gcuomo@unibas.it

ABSTRACT
Road pavements are those structural elements subjected to loads deriving from the vehicles movement.
Amongst the different kinds of pavements normally used to withstand such loads, rigid elements are supposed to be the most suitable for those conditions where severe stresses are supposed to be experienced . They are made of concrete and are designed in order to fulfil the following requirements:

- Guarantee a regular and poorly deformable rolling surface for vehicles;
- Distribute the vehicles loads among the different areas of the ground, thus avoiding undesired deformations;
- Save the ground underneath the upper layer from environmental actions.

This paper deals with some special aspects of rigid pavements: in particular, fibre reinforced concrete elements have been tested at the Laboratory of Roads Construction of the University of Basilicata, analysing their behaviour in different situations: in particular, only the aspect connected with the impact resistance will be mentioned at this stage, the performances of different pavements reinforced with various kinds of fibres (metallic and synthetic) being therefore highlighted.
Impact resistance tests were performed both at 7 and 28 days, so that all the aspects connected with the rupture of the element (first crack, number and width of cracks at different stages) were perfectly studied.
Moreover, some *Impact Resistance Indices* were defined, in order to correctly characterise the elements during the three following stages of cracking: initial, intermediate and final, corresponding to collapse.
The laboratory experiments drove to significant consideration on fibre reinforced concrete pavements, allowing the writers to make a clear comparison amongst the different kind of fibres used: indeed, the behaviour of pavements changed with composition (steel or polymer modified), dimensions (length and aspect ratio) and dosage of fibres, demonstrating that, nowadays, there is no kind of fibre that can guarantee a better behaviour in every circumstances.

Keywords: rigid pavements, fibre reinforced concrete, steel fibres, polymer modified fibres, Marshall hammer first crack, final crack, impact resistance, impact resistance indices.

1 INTRODUCTION

1.1 Engineering issues

It is well known that short fibres randomly distributed into a concrete matrix generally increase the performances of a structural element; these improvements are mostly experienced after first crack occurs, as fibres start working after this stage, spreading the loads along the whole structure.
The impact resistance of a concrete pavement will be improved as well if fibres are added into the paste, and this increase in performances will depend upon several factor, as it will be stated further.
Several concrete pavements were tested at the Laboratory of Roads Construction of the University of Basilicata (Potenza, Italy) in order to assess their performances from the point of view of the impact resistance.
The comparison of plain and fibre reinforced concrete structural elements was the leading point of the research; nevertheless, different sets of fibres were used, from the point of view of material, dimension and dosage.
As a matter of fact, the following concrete specimens (d = 8 cm, h = 16 cm) were tested:

- Plain (as reference);

- Reinforced with 30 mm steel fibres (20 Kg/m^3);
- Reinforced with 60 mm steel fibres (20 Kg/m^3);
- Reinforced with new polymer modified PMF fibres (10 Kg/m^3);
- Reinforced with new polymer modified PMF fibres (20 Kg/m^3);

2 LABORATORY EXPERIMENTS

2.1 Casting of specimens

One batch of concrete was prepared for all the specimens, and then the exact quantities of fibres added each time, so that every changes in the performances would only depend on the addition of fibres and not on the different quality of the paste.

Thirty specimens were manufactured: three for each set, considering both the different kinds of fibres and the different seasoning times (7 and 28 days).

2.2 Materials used for the experiments

2.2.1 Mix, cement and concrete

Table 1 shows all the characteristics of mix and cement, and of the concrete so prepared.

2.2.2 Fibres

As already stated, two different kinds of fibres were used for the purpose of the research: steel and polymer modified fibres PMF, the latter being rather innovative from the point of view of both the manufacturing process and the mechanical performances.

The metallic fibres were employed in two different sizes, always with the same dosage, while a unique kind of PMF, in two different dosages, was used; Table 2 includes all the features of these fibres.

2.2.3 Additive

In order to improve the workability and the uniformity of the paste, a superplasticizer product was added into the concrete matrix, the main features being described as follows:

- Dosage: 1.1% on the cement weight;
- Density: 1.21 ± 0.02;
- pH : 7.5 ± 1;
- Chlorides content: 0.

2.3 Impact resistance assessment experiments

The aim of this test was the assessment of the different behaviour amongst the various kinds of pavements in case of cyclic impacts, after 7 and 28 days of seasoning, starting from the general idea that, in any case, the performances of fibre reinforced concrete pavements should be better than the plain concrete ones.

2.3.1 Norms and prescriptions

The ACI 544 (*American Concrete Institute*) procedure was followed for this purpose, measuring the number of impacts needed for the material to get to first crack and to collapse.

2.3.2 Devices used for the experiments

The Marshall hammer, normally used for bituminous binder specimens, was used for the execution of the test. Obviously, it was opportunely modified in order to fulfil the requirements of the above mentioned Norm, as it can be seen in Figure 1.

2.3.3 Execution of the test

According to the ACI 544 procedure, the test finished when, after a certain number of impacts, the specimen opened up to a certain limit.

Figures 2 and 3 explains the different shape of the specimens at the end of the test; in the first case, plain concrete, the element was characterised by a fragile rupture, concentrated just in one spot of the specimen itself. On the contrary, in case of fibre reinforced concrete specimens (Figure 3), a radial path was experienced for the cracks; this is the evidence of the fact that, after first crack occurs, fibres re-distribute stresses along the whole structure, the material being therefore more ductile.

The following stage of the research, therefore, was concentrated on the assessment of this improvement, comparing the different kinds of fibres.

2.4 Results

2.4.1 First crack strength

Looking at the number of impacts for first crack, it was evident that, as expected, plain structures had the worst behaviour after both 7 and 28 days.
In any case, the improvements experienced for fibre reinforced specimens with respect to first crack strength were rather limited: this is the evidence of the fact that fibres start working especially after first crack occurs and not before. Table 3 highlights the results for both seasoning times.

2.4.2 First crack width

From this point of view, the first consideration was that the seasoning time played an important role in the concrete strength, as the first crack width was lower for the specimens which could season for a longer period.
Moreover, it was found that no significant improvement was experienced because of the presence of fibres, which strengthened the theory that fibres only work after first crack.
These results are included in Table 4.

2.4.3 Collapse resistance

This was one of the aspects for which very important results were found as, actually, fibre reinforced concrete pavements showed a better behaviour than plain concrete ones.
Moreover, not all fibres behaved the same, the differences being explained in Table 5. In this case improvements were experienced for both seasoning times.

2.4.4 Crack width as function of number of impacts

The results of the tests allowed the drawing of the charts in Figures 4 and 5, which show the crack width as function of the number of impacts, as usual, for the different seasoning times.
In order to understand the behaviour of the various material starting from these graphs, one should consider that the more the curve is parallel to the x axis, the worse the mechanical performances of the structural element: in other words, the larger the area underneath the curve, the more ductile is the pavement.

3 DETERMINATION OF THE IMPACT RESISTANCE INDICES

Starting from the ASTM C 1018-97 procedure (*Standard Method for Flexural Toughness and First-Crack Strength of Fiber Reinforced Concrete*), which allows the evaluation of toughness of a fibre reinforced material by means of the assessment of specific indices, the writers decided to make a proposal on the definition of brand new indices based on the impact resistance of the material, called ***Impact Resistance Indices***, which would reflect the real behaviour of the concrete pavements during the various stages of cracking: initial, intermediate and final (just before collapse) cracking.
In particular, these indices were calculated dividing the area underneath the curve crack width-number of impacts, measured for a specific value of the crack width, by the area measured underneath the same curve for the first crack width δ.
Conventionally, the following specific values were considered for the above mentioned measurement: 3δ, 5.5δ e $\delta_{collapse.}$, respectively for the ***Initial Impact Resistance Index***, the ***Intermediate Resistance Index*** and the ***Final Resistance Index*.**
Figure 6 schematically explains the way these indices were calculated.
Labelling with A_δ, $A_{3\delta}$, $A_{5.5\delta}$ and $A_{\delta.collapse}$, the above mentioned areas, with obvious meaning of the symbols, the indices were thus defined as follows:

- *Initial Impact Resistance Index*: $I_{rui} = \frac{A_{3\delta}}{A\delta}$;
- *Intermediate Impact Resistance Index*: $I_{rum} = \frac{A_{5.5\delta}}{A_\delta}$;
- *Final Impact Resistance Index*: $I_{ruf} = \frac{A_{\delta\, collapse}}{A_\delta}$.

Eventually, by means of these indices one could perfectly understand the different performances of fibre reinforced concrete pavements, varying with the different kinds and quantity of fibres used; obviously, these performances can be divided into sets of results referring to the various stages of cracking, from initial cracking to collapse.

3.1 Comparison of the results

Table 6 simply contains the values found for each index above defined, for each set of specimens and for the different seasoning times. The same results are also included in the charts of Figures 7 and 8, respectively after 7 and 28 days.
A first glance would doubtless reveal the dramatic increase in performances during the last part of cracking for all the sets of fibre reinforced pavements, no matter the kind and the dosage of the micro-elements, but a deeper analysis would tell that not all the fibres behave the same.
In any case, after the test, it is clear that fibre reinforced concrete pavements can withstand more and more loads after first crack, while similar plain elements would suddenly collapse, without great hopes.

4 Conclusions

The large set of results obtained during the research would probably make difficult the writing down of concise conclusions. In order to keep them to the minimum some matrices were used for the relative assessment of the performances of the various pavements, at different seasoning times, during the different stages of rupture.
The plain concrete element was considered as reference, giving it the lower relative value (indicated with “O”).
For the fibre reinforced pavement stars (“*”) were used for the assessment of performances: the higher the number of stars, the better the behaviour for that specific aspect.
Table 7 explains the method adopted for this purpose, while all the results are schematically included in Table 8.
Generally speaking, these results can be divided into the following three parts:

- Initial cracking
- Intermediate cracking
- Final cracking (collapse)

4.1 Initial crack strength

1. Steel fibres in general showed a better behaviour than PMF fibres after 7 days. At 28 days, the situation was exactly the opposite;
2. Amongst the steel fibres, the 30 mm long, for short seasoning, behaved better than the 60 mm ones;
3. for PMF fibre reinforced concrete pavements, the higher the dosage, the better the performances;
4. no matter the seasoning time, during this phase of cracking pavements with high quantities of PMF fibres (20 kg/m^3) revealed a better behaviour than all the other structural elements.

4.2 Intermediate crack strength

1. significant was the behaviour of the pavements reinforced with the 30 mm long steel fibres;
2. 60 mm steel fibres pavements did not reach the performances of the similar elements reinforced with 30 mm steel fibres;
3. the higher the dosage of PMF fibres, the faster the element in reaching its performances: for 20 kg/m^3 PMF fibres pavements, indeed, the performances after 7 days are very similar to those after 28 days, while this pattern will change if a lower quantity of fibres (10 kg/m^3) is used;
4. no matter the seasoning time, during this phase of cracking pavements with high quantities of PMF fibres (20 kg/m^3) revealed a better behaviour than all the other structural elements.

4.3 Final crack strength

1. 30 mm steel fibres did not seem to reveal the same good pattern as before, the pavements performances dramatically collapsing;
2. the behaviours of the pavements with 60 mm long steel fibres and with 10 kg/m^3 PMF fibres are similar and definitely better than 30 mm steel fibres one;
3. The increased dosage of PMF fibres strongly improves the performances of pavements during the last stage of cracking, before collapsing.
4. In particular, this increment can be already measured after 7 days of seasoning, when most of the performances measured at 28 days are already reached.

4.4 Overall conclusions

Referring to the above described tests and to the 20 kg/m^3 PMF fibres pavements, one must admit that the use of the new particular synthetic micro-elements inside the concrete matrix involves a significant increase in the mechanical performance of the structural element from the point of view of the impact resistance.

Nevertheless, it is undoubted that a similar pattern, reduced but definitely better than plain concrete pavements can be reached by using the cheaper 60 mm long steel fibres.
Generally speaking, the use of one kind of fibres instead of another should be deduced from both the required performance level and the time, from the point of view of seasoning, when these performances are needed.
In conclusion, the authors believe that at the moment there is no small fibre which would guarantee the best performances ever for concrete pavement structures: it is up to the designer to choose for every kind of project the appropriate suitable solution.

REFERENCES

1. Agostinacchio M., Bernetti R., Diomedi M., "*Analisi delle caratteristiche superficiali di aderenza e regolarità delle sovrastrutture stradali urbane mediante definizione di una indice di efficienza globale (IEG)*", Atti della giornata di studio sul tema: Sicurezza intrinseca delle infrastrutture stradali, Roma, 20 – 21 Febbraio 1997.
2. Agostinacchio M., Cuomo G., Olita S., "*Pavimentazioni in calcestruzzo fibro-rinforzato: analisi agli elementi finiti e comportamento post-rottura*", L'Industria Italiana del Cemento - Anno LXXIII – Numero 785, Roma, Marzo 2003.
3. Agostinacchio M., Cuomo G., Olita S., **"***Finite element and post-crack analysis of fiber reinforced concrete pavement structures***"** , 9th International Symposium on Concrete Roads, Istanbul, Turkey, Aprile 2003 .
4. Agostinacchio M., Cuomo G., **"***Polymer modified and steel fibre reinforced concrete pavements : assessment of toughness and residual strength***"**, CONCRETE Magazine, Crowthorne, Berkshire, Great Britain, Settembre 2003.
5. Agostinacchio M., Cuomo G., *"Early shrinkage behaviour and de-icing salts resistance of plain and fibre reinforced concrete pavements"* , Sixth RILEM Symposium on Fibre Reinforced Concrete (FRC) BEFIB 2004, Varenna (CO), Italy, Settembre 2004 (to be publishing)
6. Bayasi Z., Zemp J., "*Properties of Polypropylene Fiber Reinforced Concrete*", ACI Materials Journal, Vol. 90, Issue 6, Detroit, 1993.
7. Bentur A., Mindness S., "*Fiber Reinforced Cementitions Composites*", Elsevier Appield Science, London & New York, 1990.
8. CNR, "*Catalogo delle Pavimentazioni Stradali*", B. U. n° 178, 1995.
9. Collepardi S., Coppola L., Troli R., "*Pavimentazioni Industriali in Calcestruzzo*", Enco, Spresiano (TV), Settembre 1998.
10. Cuomo G. , "Assessment of the uniformità of density of concrete in the wake of a steel cylinder", MSc Thesis, Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin, Ireland, 1997.
11. Cuomo G., West R.P., "*Pavimentazioni in calcestruzzo fibrorinforzato: allineamento delle fibre in campo magnetico*", Enco Material Journal, Anno VII - Numero 20, Spresiano (TV), Italy, September 2002.
12. Cuomo G., **"** *Utilizzo delle fibre di rinforzo all'interno delle pavimentazioni rigide: tecnologia, modello di calcolo ed analisi sperimentale***"**, Tesi di Dottorato di Ricerca in Infrastrutture di Viabilità e Trasporto, Università degli Studi della Basilicata, Potenza, Italia, Aprile 2003.
13. Domenichini L., "*Pavimentazioni Stradali in Calcestruzzo, Progettazione, Esecuzione, Manutenzione*", A.I.T.E.C., 1984.
14. Hannant D. J. , Edgington J. , "*Durability of steel fiber concrete*", in Fiber Reinforced Cement and Concrete, Proceedings, RILEM Symposium, The Construction Press, UK 1975.
15. Knapton J., "*Single Pour Industrial Floor Slabs*", Thomas Telford Publishing, Thomas Telford Limited, London, England, 1999.
16. Shah S. P., Rangan V. B., "*Fiber Reinforced Concrete Properties*", ACI Journal, Vol. 68, Detroit, 1971.
17. Shah S. P. , "*Concrete and fiber reinforced concrete subjected to impact loading*", in Cement- based Composites: Strain Rate Effects on Fracture, ed. S. Mindess & S. P. Shah, Materials Research Society Symposium Proceedings, Vol. 64, Materials Research Society, Pittsburgh, 1986.
18. Shah S.P., Skarendahl, "*Steel Fiber Concrete*", Elsevier Appield Science, London & New York, 1986.
19. Swamy R. N. , Stavrides H. , "*Influence of fibre reinforcement in restrained shrinkage and cracking*", J. Materials Science, 19, 1984.
20. Tawfiq K., Amaghani J., Ruiz R., *"Fatigue Cracking of Polypropylene Fiber Reinforced Concrete"*, ACI Materials Journal Vol.96 - Issue 2, American Concrete Institute, Detroit 1999.
21. West R.P., "The alignment of steel fibers in concrete slabs using permanent magnets", Munro Centre Seminar, UNSW, Sydney, 2000.
22. West R.P., Callan J.M., *"Drying shrinkage characteristics of industrial ground floors reinforced with aligned steel fibers"*, Confidential Tech. Rpt. to Readymix Ltd, Dublin, Ireland, 2000.
23. West R.P., Pull M., "Flexural strength of aligned steel fibres reinforced concrete", Confidential Tech. Rpt. to Readymix Ltd, Dublin, Ireland, 2000.
24. West R.P. e Cuomo G. , *"Strength Loss in the Wake of a Steel Cylinder Dragged through a Concrete Slab"*, in "Concrete Research in Ireland – Proceedings of the 2001 Colloquium", Eamonn P. Cannon Editor, Galway, 2001.
25. West R.P., *"Design issues in the alignment of steel fibers in concrete slabs using a magnetic fin"*, International Congress on Challenges of Concrete Construction, Dundee, 2002.

NORMS AND PRESCRIPTIONS

1. ACI Committee 544, "*State of the Art Report on Fiber Reinforced Concrete*", ACI Manual of Concrete Practice, Part 5, American Concrete Institute, Detroit, 1990.
2. ACI Committee 544, "*Guide for Specifying, Proportioning, Mixing, Placing and Finishing Steel Fiber Reinforced Concrete*", ACI Materials Journal, Vol 90, N. 1, Detroit, 1993.
3. American Society for Testing and Materials, "*C1018-97 Standard Test Method for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete*", West Conshohocken, PA, 2001.
4. American Society for Testing and Materials, *"C39/C39M-01 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens"*, West Conshohocken, PA, 2001.
5. American Society for Testing and Materials, *"C78-02 Standard Test Method for Flexural Strength of Concrete"*, West Conshohocken, PA, 2001.
6. ATECAP, "*Prescrizioni per il calcestruzzo. Caratteristiche dei costituenti e delle miscele, produzione, trasporto, controllo, posa in opera e stagionatura del calcestruzzo*", 1998.
7. ENV 206, "*Calcestruzzo: prestazioni, produzione, getto e criteri di conformità*", 1989.
8. Presidenza del Consiglio Superiore dei Lavori Pubblici, Servizio Tecnico Centrale, "*Linee guida sul calcestruzzo strutturale*", Dicembre 1996.
9. UNI 6127, "*Provini in calcestruzzo per le prove di resistenza. Preparazione e stagionatura*", Maggio 1998.
10. UNI 6130-I, "*Provini di calcestruzzo per prove di resistenza meccanica. Forma e Dimensioni*", Settembre 1980.
11. UNI 9858, "*Calcestruzzo. Prestazioni, produzione, posa in opera e criteri di conformità*", 1991.
12. UNI EN 206-1, "*Calcestruzzo: Specificazione, prestazione, produzione e conformità*", Ottobre 2001.

LIST OF TABLES

TABLE 1: Characteristics of mix, cement and concrete
TABLE 2: Characteristics of the fibres used for the experiments
TABLE 3: Impacts needed for first crack to occur
TABLE 4: First crack width
TABLE 5: Number of impacts for collapse
TABLE 6: values of the Impact Resistance Indices
TABLE 7: guide for the assessment of the relative performances of the various pavements
TABLE 8: relative assessment of the performances of all the pavements, for the different seasoning times, during the various stages of cracking.

LIST OF FIGURES

FIGURE 1: The modified Marshall hammer used for the tests
FIGURE 2: A plain concrete specimen at the end of the test
FIGURE 3: A fibre reinforced concrete specimen at the end of the test
FIGURE 4: Crack width as function of number of impacts, after 7 days of seasoning
FIGURE 5: Crack width as function of number of impacts, after 28 days of seasoning.
FIGURE 6: Conventional values chosen for the measurement of the Impact Resistance Indices
FIGURE 7: values of the Impact Resistance Indices, after 7 days of seasoning (respectively, from the left hand side, I_{rui}, I_{rum}, I_{ruf})
FIGURE 8: values of the Impact Resistance Indices, after 28 days of seasoning (respectively, from the left hand side, I_{rui}, I_{rum}, I_{ruf})

CHARACTERISTICS OF THE MIX	**Fine sand**	300 (kg/m^3)
	Sand	500 (kg/m^3)
	Crushed stone 2-20 mm	640 (kg/m^3)
	Crushed stone 20-32 mm	560 (kg/m^3)
CHARACTERISTICS OF CEMENT	**Kind of cement**	425 II/A-II
	Cement dosage	300 kg/m^3
	Water dosage	1.35 l/ m^3
	w/c ratio	0.45
CHARACTERISTICS OF CONCRETE	**Consistency**	fluid
	Absolute gravity	2300 kg/m^3
	R_{ck} (7 days)	220.16 Kg/cm^2
	R_{ck} (28 days)	277.67 Kg/cm^2

TABLE 1: Characteristics of mix, cement and concrete

CHARACTERISTICS OF THE FIBRES USED		
30 MM STEEL FIBRES	**Length**	30 mm
	Diameter	0.60 mm
	Aspect ratio	50
	Section	0.28 mm^2
	Tensile strength	360 – 410 MPa
	Dosage	30 kg/m^3
60 MM STEEL FIBRES	**Length**	60 mm
	Equivalent diameter	0.75 mm
	Aspect ratio	80
	Section	0.44 mm^2
	Tensile strength	1050 MPa
	Dosage	30 kg/m^3
PMF FIBRES	**Material**	Co-polymer/polypropylene
	Shape	Monofilament/fibrillated
	Acid resistance	Total
	Specific weight	0.91 kg/dm^3
	Tensile strength	620 - 758 MPa
	Length	54 mm
	Equivalent diameter	0.069 mm
	Aspect ratio	782
	Dosage	10 - 20 kg/m^3

TABLE 2: Characteristics of the fibres used for the experiments

IMPACTS NEEDED FOR FIRST CRACK				
	First specimen	***Second specimen***	***Third specimen***	***Mean value***
Plain concrete (at 7 days)	4	5	5	**4.67**
Plain concrete (at 28 days)	10	9	9	**9.33**
30 mm steel fibre (at 7 days)	5	8	5	**6.00**
30 mm steel fibre (at 28 days)	9	10	8	**9.00**
60 mm steel fibre (at 7 days)	6	6	6	**6**
60 mm steel fibre (at 28 days)	11	13	12	**12**
PMF fibre – 10 kg/mc (at 7 days)	5	4	6	**5**
PMF fibre – 10 kg/mc (at 28 days)	9	10	10	**9.67**
PMF fibre – 20 kg/mc (at 7 days)	6	5	4	**5**
PMF fibre – 20 kg/mc (at 28 days)	10	11	12	**11**

TABLE 3: Impacts needed for first crack to occur

FIRST CRACK WIDTH (mm)				
	First specimen	***Second specimen***	***Third specimen***	***Mean value***
Plain concrete (at 7 days)	0.12	0.12	0.19	**0.14**
Plain concrete (at 28 days)	0.15	0.11	0.13	**0.13**
30 mm steel fibre (at 7 days)	0.21	0.15	0.18	**0.18**
30 mm steel fibre (at 28 days)	0.15	0.12	0.16	**0.14**
60 mm steel fibre (at 7 days)	0.16	0.14	0.13	**0.14**
60 mm steel fibre (at 28 days)	0.13	0.10	0.11	**0.11**
PMF fibre – 10 kg/mc (at 7 days)	0.11	0.12	0.14	**0.12**
PMF fibre – 10 kg/mc (at 28 days)	0.09	0.10	0.09	**0.09**
PMF fibre – 20 kg/mc (at 7 days)	0.07	0.11	0.25	**0.14**
PMF fibre – 20 kg/mc (at 28 days)	0.08	0.09	0.08	**0.08**

TABLE 4: First crack width

IMPACTS NEEDED FOR COLLAPSE				
	First specimen	***Second specimen***	***Third specimen***	***Mean value***
Plain concrete (at 7 days)	8	8	8	8.00
Plain concrete (at 28 days)	16	15	15	**15.33**
30 mm steel fibre (at 7 days)	11	12	12	**11.67**
30 mm steel fibre (at 28 days)	18	17	16	**17.00**
60 mm steel fibre (at 7 days)	15	14	13	**14**
60 mm steel fibre (at 28 days)	22	20	20	**20.67**
PMF fibre – 10 kg/mc (at 7 days)	15	14	14	**14.33**
PMF fibre – 10 kg/mc (at 28 days)	18	19	20	**19.00**
PMF fibre – 20 kg/mc (at 7 days)	18	17	15	**16.67**
PMF fibre – 20 kg/mc (at 28 days)	22	23	23	**22.67**

TABLE 5: Number of impacts for collapse

IMPACT RESISTANCE INDICES			
	I_{rui}	I_{rum}	I_{ruf}
Plain concrete (at 7 days)	3.28	6.21	53.90
Plain concrete (at 28 days)	3.47	7.11	63.47
30 mm steel fibre (at 7 days)	4.00	9.66	54.15
30 mm steel fibre (at 28 days)	4.15	9.80	64.50
60 mm steel fibre (at 7 days)	3.51	7.45	75.19
60 mm steel fibre (at 28 days)	3.85	9.10	87.23
PMF fibre – 10 kg/mc (at 7 days)	3.43	7.04	100.84
PMF fibre – 10 kg/mc (at 28 days)	3.81	8.94	112.10
PMF fibre – 20 kg/mc (at 7 days)	3.79	8.34	130.84
PMF fibre – 20 kg/mc (at 28 days)	4.21	9.83	148.20

TABLE 6: values of the Impact Resistance Indices

PAVEMENT	PERFORMANCE LEVEL	SYMBOL
plain	reference (fragile behaviour)	○
Fibre-reinforced	low	✳
	medium	✳✳
	high	✳✳✳

TABLE 7: guide for the assessment of the relative performances of the various pavements

ASSESSMENT OF THE PERFORMANCES OF THE PAVEMENTS			
30 mm steel fibre reinforced concrete pavement		**7 gg**	**28 gg**
First crack strength		✱✱✱	○
First crack width		○	○
Final crack strength		✱	✱
Impact resistance after first crack	I_{rui}	✱✱✱	✱✱✱
	I_{rum}	✱✱✱	✱✱✱
	I_{ruf}	○	○
60 mm steel fibre reinforced concrete pavement		**7 gg**	**28 gg**
First crack strength		✱✱✱	✱✱✱
First crack width		○	✱
Final crack strength		✱✱	✱✱✱
Impact resistance after first crack	I_{rui}	✱	✱✱
	I_{rum}	✱	✱✱
	I_{ruf}	✱	✱✱
PMF (10 kg/m^3) fibre reinforced concrete pavement		**7 gg**	**28 gg**
First crack strength		✱✱	✱
First crack width		✱	✱✱
Final crack strength		✱✱	✱✱
Impact resistance after first crack	I_{rui}	✱	✱✱
	I_{rum}	✱	✱✱
	I_{ruf}	✱✱	✱✱
PMF (20 kg/m^3) fibre reinforced concrete pavement		**7 gg**	**28 gg**
First crack strength		✱✱	✱✱✱
First crack width		○	✱✱✱
Final crack strength		✱✱✱	✱✱✱
Impact resistance after first crack	I_{rui}	✱✱	✱✱✱
	I_{rum}	✱✱	✱✱✱
	I_{ruf}	✱✱✱	✱✱✱

TABLE 8: relative assessment of the performances of all the pavements, for the different seasoning times, during the various stages of cracking.

FIGURE 1: The modified Marshall hammer used for the tests


FIGURE 2: A plain concrete specimen at the end of the test

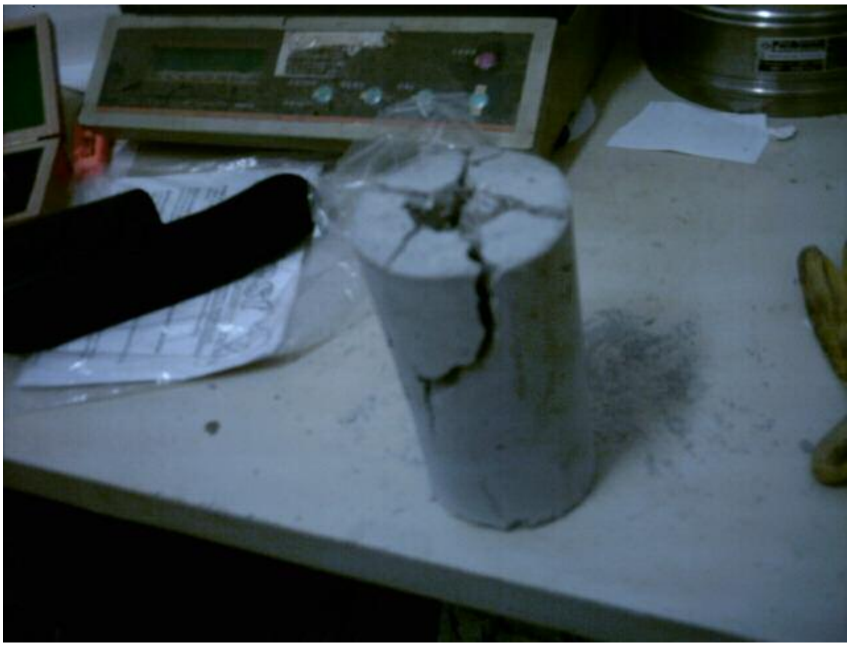
FIGURE 3: A fibre reinforced concrete specimen at the end of the test

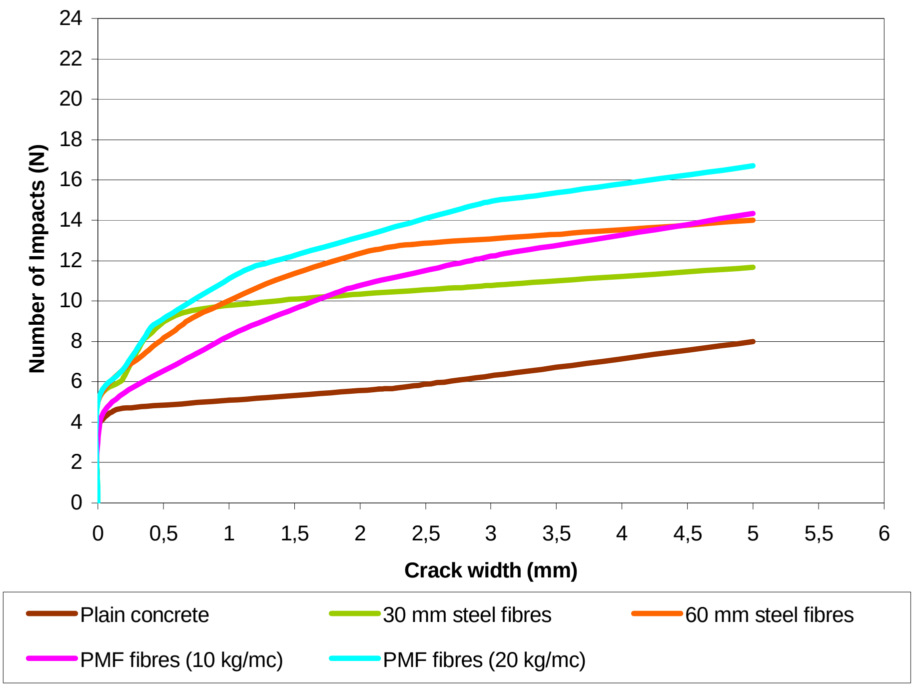

FIGURE 4: Crack width as function of number of impacts, after 7 days of seasoning

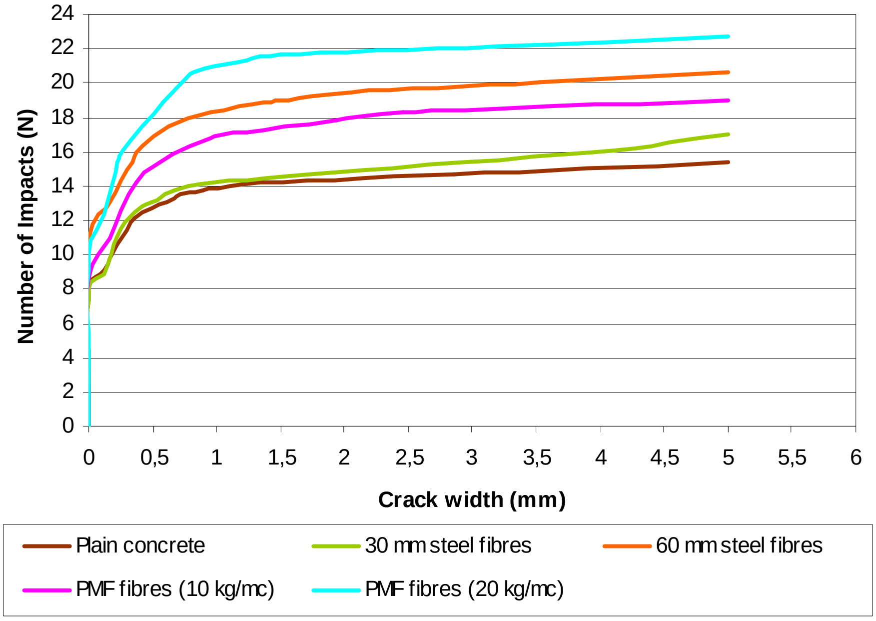

FIGURE 5: Crack width as function of number of impacts, after 28 days of seasoning.

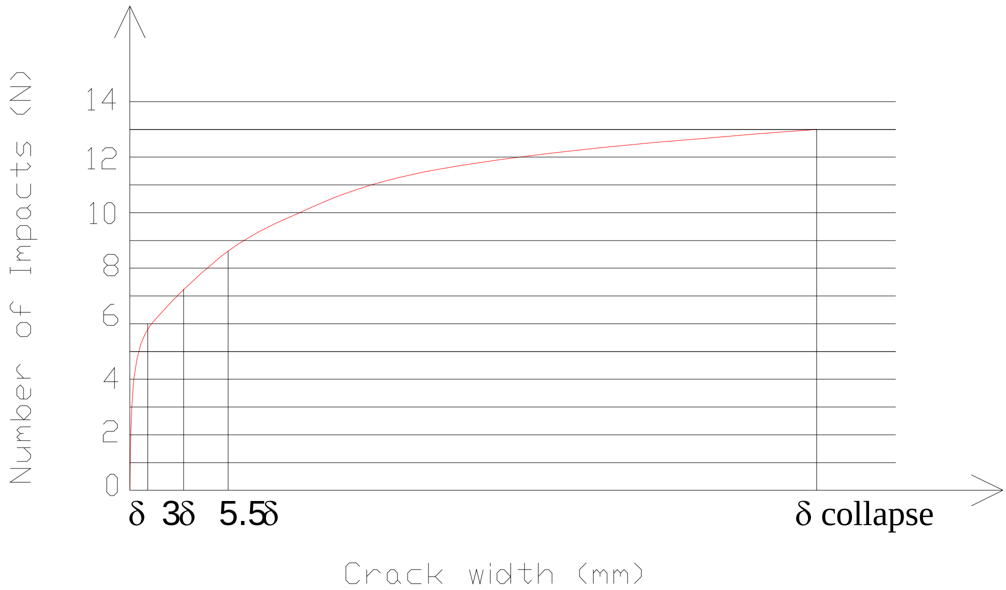

FIGURE 6: Conventional values chosen for the measurement of the Impact Resistance Indices

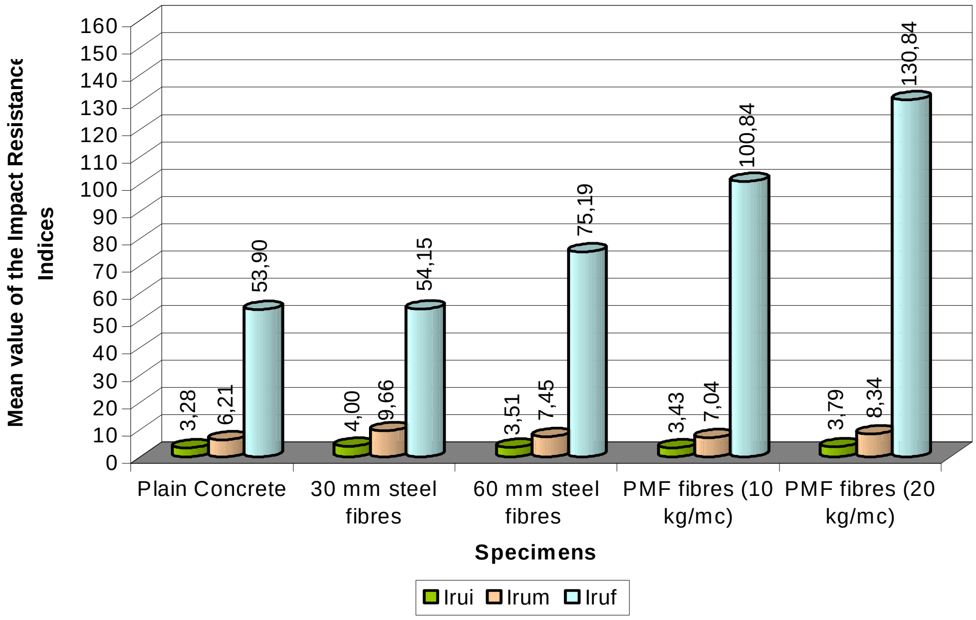

FIGURE 7: values of the Impact Resistance Indices, after 7 days of seasoning (respectively, from the left hand side, I_{rui}, I_{rum}, I_{ruf})

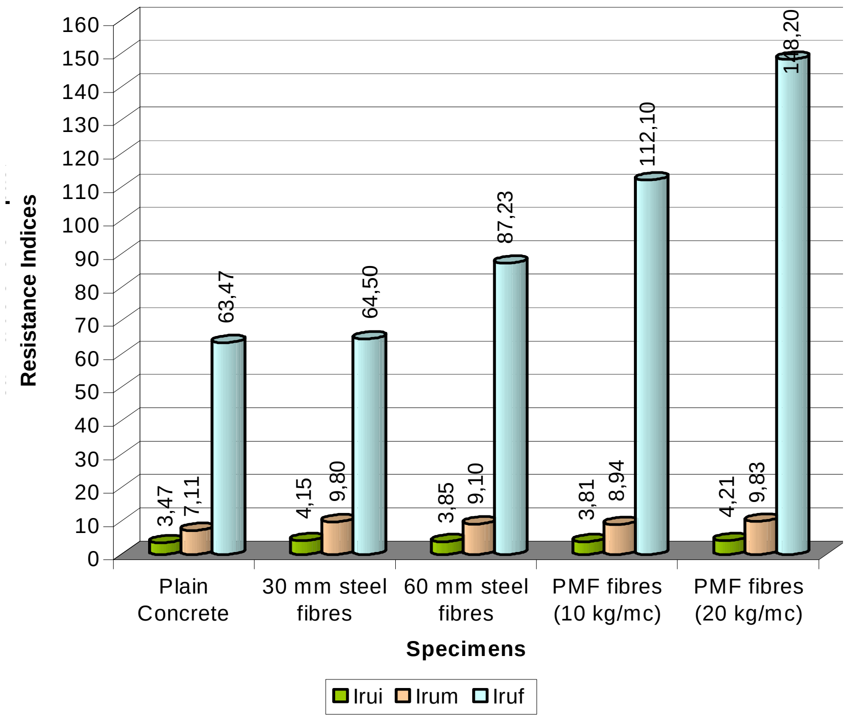

FIGURE 8: values of the Impact Resistance Indices, after 28 days of seasoning (respectively, from the left hand side, I_{rui}, I_{rum}, I_{ruf})